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Study on Optimization Strategy for Voltage and Reactive Power Control of Wind Farm

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Abstract

A method for calculating reactive power limit of wind farm comprised of doubly-fed induction generators (DFIG) is proposed. The reactive power limit of wind farm is the sum of reactive power limit of DFIGs which is calculated by the method considering static stability margin. Based on this, reactive power control of wind farm is discussed and proposed. The proposed reactive power control is divided into different control modes according to power factor of high voltage side in wind farm substation and voltage of low voltage side in point of interconnection(POI). In different control modes, different control objects are applied on reactive power regulation. After reactive power regulation is finished, some reactive power of wind farm should be released. At last, numerical test system is established, the result shows that the proposed method is effective to support voltage of POI.

Keywords:wind power; reactive power limit; reactive power control; cooperation and optimization.

1.Introduction

WITH large scale wind power integrated into grid, its impacts on gird stability has been an important issue. Because wind farm is at the terminal of grid usually, wind farm reactive power command and loss are bigger so that it may impact on voltage level and stability margin.

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To solve the issue, two areas need be studied. One is how to regulate reactive power output of wind turbines by the decoupling control method shown in Ref[1]. The other is how to control reactive power output of wind farm to make it track with voltage of POI.

Recently, many scholars have studied on DFIG control technologies. Reactive power limit of DFIG with constraints and layered control strategy are proposed in [2]-[4]. A method of reactive power control and distribution based on PI controller is proposed in [5]. Also, many scholars have studied reactive power control strategy from the point of cooperation between wind farm and grid. A strategy for reactive power control of wind farm considering district grid reactive power command is researched in [6]. A strategy for wind farm reactive power control according to voltage at high side of POI is proposed in [7]-[8]. A method of assessing static reactive power/voltage supporting ability is proposed in [9]-[10]. Layered Var control strategy of DFIG-based wind farm is proposed in [11]-[14].

However, above methods all selects voltage as control objects. To improve the control strategy, a new strategy considering that POI voltage and power factor are both selected as control objects is proposed. The analysis of reactive power limit is described in Section II, basic idea is described in Section III, reactive power compensation capacity calculation is described in Section IV, and the numerical analysis in Section V. Finally, the conclusions are drawn in Section VI.

2.Analysis of Reactive Power Limit

It is indicated that power output at stator side is limited by stator windings current, rotor windings current and current of rotor side converter, and the most important is the current of rotor side converter. It can be described as

$$P_s^2 + (Q_s + \frac{\left|\dot{U}_s\right|^2}{X_{ss}})^2 \le \frac{\left|\dot{U}_s\right|^2 x_m^2}{X_{ss}^2} I_{r\max}^2 \qquad (1)$$

Where, P_s is stator active powe, Q_s is stator reactive power, U_s is stator voltage, x_m is exciting resistance, $I_{r\max}$ is the maximum current limit of converter, $X_{ss}=x_s+x_m$.

Though DFIG is asynchronous generator, from the point of electromagnetic, if mechanical power is larger than electromagnetic power, it will lead power angle to increase. Then it may damage static stability like synchronous generator when grid disturbances. So it is essential to consider static stability margin when reactive power limit of DFIG is analyzed. Assuming that static stability margin coefficient is described as

$$K_{sm} = \frac{P_{\max} - P_e}{P_e} \times 100\% \qquad (2)$$

Also power angle characteristic of DFIG is shown in Fig.1.

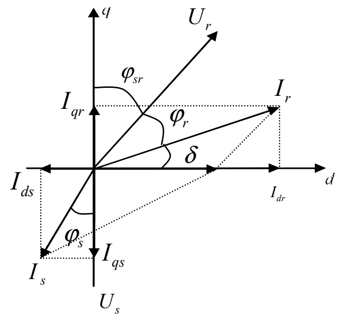


Fig. 1 Power angle characteristic of DFIG .

Also power angle characteristic of DFIG is shown in Fig.1. From Fig.1 the power angle of DFIG can be expressed as

$$\delta = \arctan\frac{I_{qr}}{I_{dr}} \tag{3}$$

Further electromagnetic power of DFIG can be expressed as

$$P_e = X_m \frac{U_s}{X_{ss}} X_m I_r \sin\delta \tag{4}$$

Where, X_mI_r is non-load electromotive force E_q, so equation (4) can be expressed as

$$P_e = \frac{E_q U_s}{X_{ss}} \sin\delta \tag{5}$$

From above equation, it can be seen that electromagnetic power of DFIG is the same with synchronous salient-pole generator. Assuming that power angle of DFIG ranges from $\delta_{\min}$ to $\delta_{\max}$, it is corresponding that their tangent values are $K_{\min}$ and $K_{\max}$ respectively. So stator power can be described as

$$\begin{cases} P_s = \dfrac{|U_s| X_m I_{qr}}{X_{ss}} \\ Q_s = |U_s|(\dfrac{|U_s| - X_m I_{dr}}{X_{ss}}) \end{cases} \tag{6}$$

According to equation (3) and (6), stator reactive power should meet below equation which is reactive power limit considering static stability margin,

$$\frac{P_s X_{ss} - K_{\max}|U_s|^2}{K_{\max} X_{ss}} \le Q_s \le \frac{P_s X_{ss} - K_{\min}|U_s|^2}{K_{\min} X_{ss}} \tag{7}$$

Then stator reactive power limit can be derived by equation (1) and (7),

$$\begin{cases} Q_{s\min} = \dfrac{P_s X_{ss} - K_{\max}|U_s|^2}{K_{\max} X_{ss}} \\ Q_{s\max} = \min\{\dfrac{P_s X_{ss} - K_{\min}|U_s|^2}{K_{\min} X_{ss}}, \\ -\dfrac{|U_s|^2}{X_{ss}} + \sqrt{\dfrac{|U_s|^2 X_m^2}{X_{ss}^2} I_{r\max}^2 - (\dfrac{1}{1-s} P_e)^2}\} \end{cases} \tag{8}$$

Additionally, dynamic continuous reactive power regulation ability of grid side converter should be considered and its ability is limited by its volume,

$$-\sqrt{S_{\mathrm{cmax}}^2 - P_{\mathrm{c}}^2} \le Q_c \le \sqrt{S_{\mathrm{cmax}}^2 - P_{\mathrm{c}}^2} \tag{9}$$

Where, $S_{c\max}$ is the volume of grid side converter, P_c is slip power through grid side converter, Q_c is reactive power generated by grid side converter.

Finally, reactive power limit of DFIG can be expressed as,

$$\begin{cases} Q_{\max} = Q_{s\max} + Q_{c\max} \\ Q_{\min} = Q_{s\min} + Q_{c\min} \end{cases} \tag{10}$$

Also, the reactive power limit based on Gamesa G52 coefficients is shown in Fig.2.,

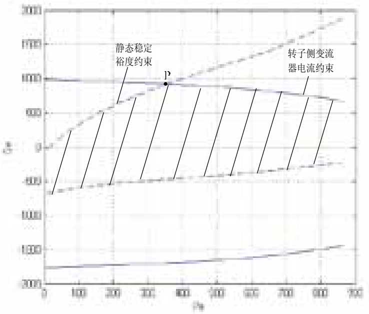


Fig. 1 Reactive power limit based on Gamesa G52 coefficients .

Because the factors which impact on power output of wind farm is so many, this paper assumes that the number of wind turbines in wind farm is n and all wind turbines operate in the same condition. Based on this, the reactive power limit of wind farm can be expressed as

$$\begin{cases} Q_{T\max} = nQ_{\max} \\ Q_{T\min} = nQ_{\min} \end{cases} \tag{11}$$

3.Basic Idea

Usually, reactive power control of wind farm should be divided into two layers, reactive power compensation capacity calculation and distribution. The former can be calculated according to POI voltage and power factor.

Because POI voltage is coupled with power factor, the cooperation between them should be considered. In detailed execution, it is first to maintain POI voltage stability and regulating power factor only when voltage is normal. The reactive power can be regulated in different partitions as shown in Fig.3.

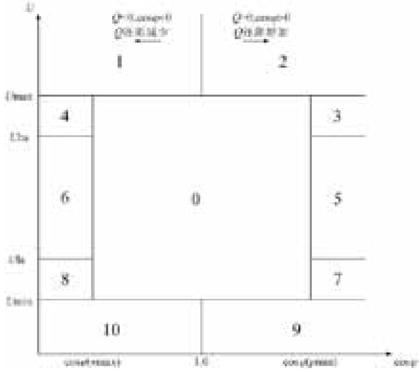


Fig. 2 The partition diagram of Var optimization control.

Where, $U_{\max}$ is maximum POI voltage, $U_{\min}$ is minimum POI voltage, U_{ha} is maximum alarm POI voltage, U_{la} is mimimum alarm POI voltage, $\cos\varphi_{p\min}$ minimum power factor, $\cos\varphi_{n\max}$ is maximum power factor.

The detailed strategy is below.

Partition 0: $U_{\min}<U<U_{\max}$. Power factor meets the command, so reactive power is not regulated.

Partition 1: $U>U_{\max}$. Reactive power is decreased.

Partition 2: $U>U_{\max}$. Reactive power is decreased.

Partition 3: $U_{\mathrm{ha}}<U<U_{\max}$, $0<\cos\varphi<\cos\varphi_{p\min}$. Decreasing reactive power will not lead that POI voltage exceed the limit, so reactive power is decreased.

Partition 4: $U_{\mathrm{ha}}<U<U_{\max}$, $0>\cos\varphi>\cos\varphi_{n\max}$. Increasing reactive power may lead that POI voltage exceed the limit, so reactive power is not regulated.

Partition 5: $U_{\mathrm{la}}<U<U_{\mathrm{ha}}$, $0<\cos\varphi<\cos\varphi_{p\min}$. Reactive power is decreased.

Partition 6: $U_{\mathrm{la}}<U<U_{\mathrm{ha}}$, $0<\cos\varphi<\cos\varphi_{p\min}$. Reactive power is increased.

Partition 7: $U_{\min}<U<U_{\mathrm{la}}$, $0<\cos\varphi<\cos\varphi_{p\min}$. Decreasing reactive power may lead that POI voltage exceed the limit, so reactive power is not regulated.

Partition 8: $U_{\min}<U<U_{\mathrm{la}}$, $0>\cos\varphi>\cos\varphi_{n\max}$. Increasing reactive power will not lead that POI voltage exceed the limit, so reactive power is increased.

Partition 9: $U<U_{\min}$. Reactive power is increased.

Partition 10: $U<U_{\min}$. Reactive power is increased.

4.Reactive powet compensation capacity caculation

Firstly, reactive power control partition is selected. Then if partition 0, 4 or 7 is selected, reactive power compensation capacity is 0. If partition 1, 2, 9 or 10 is selected, reactive power compensation capacity can be calculated according to

$$\Delta Q = S \cdot (U - U_{ref}) \tag{12}$$

Where, S is short circuit volume of POI, U is real-time POI voltage, U_{ref} is reference POI voltage.

If partition 3 or 7 is selected, reactive power compensation capacity can be calculated according to

$$\Delta Q = \min\{\frac{\sqrt{1-\lambda_{p\min}^2}}{\lambda_{p\min}} P - Q, S \cdot (U_{\min} - U_{ref})\} \tag{13}$$

Where, λ_{pmin} is the limit of positive power factor, P is real-time active power at high voltage side of POI,

U_{min} is the lower voltage limit of POI voltage.

If partition 6 or 7 is selected, reactive power compensation capacity can be calculated according to

$$\Delta Q = \min\{\frac{\sqrt{1-\lambda_{nmax}^2}}{\lambda_{nmax}}P - Q, S\cdot(U_{\max} - U_{ref})\} \quad (14)$$

Where, λ_{nmax} is the limit of negtive power factor, U_{max} is the upper voltage limit of POI voltage.

After ΔQ is calculated, reactive power output of wind farm should be compared with its limit, so reactive power output of wind farm should meet

$$Q_{reg} = \begin{cases} \min\{Q+\Delta Q, Q_{\max}\} & U > U_{\max} \\ \max\{Q+\Delta Q, Q_{\min}\} & U < U_{\min} \end{cases} \quad (15)$$

It is to be illustrated that reactive power output of wind farm should recover back to original state after grid voltage recovered to maintain enough reactive power regulation capacity in the condition that it will not damage grid voltage stability. It is assumed that POI voltage as U_{reg}. After fault is cleared, if $U>U_{max}$ and $\Delta Q<0$, reactive power can be recovered is calculated according to

$$\Delta Q_{rec}=\min\{-\Delta Q,\ (U_{max}-U_{reg})/S\} \quad (16)$$

Also, if $U<U_{min}$ and$\Delta Q>0$, reactive power can be recovered is calculated according to

$$\Delta Q_{rec}=\max\{-\Delta Q,\ (U_{min}-U_{reg})/S\} \quad (17)$$

In order to avoid POI voltage exceeding the limit caused by reactive power recovering. Recovering coefficient α is set. So reactive power output of wind farm can be recovered to

$$Q_{rec}=Q_{reg}+\alpha\Delta Q_{rec} \quad (18)$$

5.Numerical test

5.1.Test System Introduction

Test system is shown in Fig.3. Wind farm composed of ten wind turbines whose capacity is 1.5MW interconnects into grid through three feeders to substation. Coefficients of wind turbine model, lines and transformers are shown in appendix respectively.

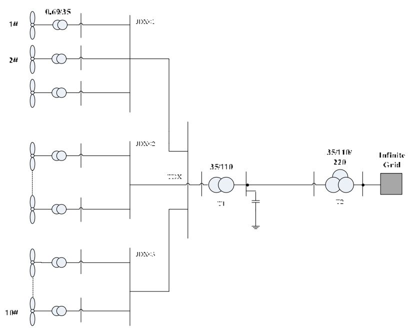


Fig. 3 Test system.

In this test system, reactive power control is simulated by proposed strategy in the condition that short circuit fault occurs at high voltage side of substation, and the result will be compared to that without applying the proposed strategy. Simulation time is set to 100 s. Power factor ranges from −0.98 to 0.98. Voltage ranges from 0.95 to 1.05p.u.. Recovering coefficient is set to 1.

5.2.Simulation

Assuming that short circuit fault occurs at high voltage side of substation at 5s and is cleared at 5.5s, if original reactive power output of wind farm is 0, POI voltage curves without reactive power regulation is shown in Fig.4 and that with reactive power regulation by proposed strategy is shown in Fig.5.

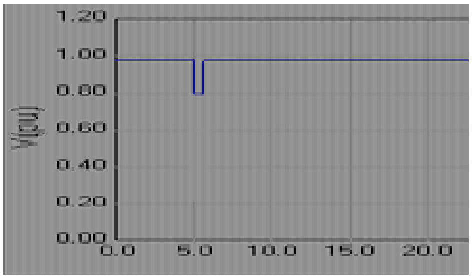
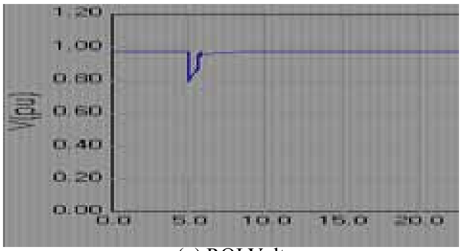
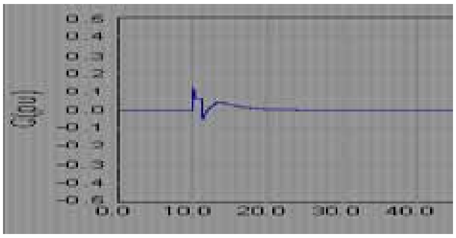


Fig. 4 Curves without reactive power control.



(a) POI Voltage



(b) Reactive Power

Fig. 5 Curves with reactive power control by proposed strategy.

From Fig.4, it is seen that original POI voltage is 0.98p.u., when short circuit occurs, POI voltage sags to 0.8p.u and recovers after fault is cleared. Comparing Fig.4 with Fig.5, it is seen that wind farm generates 0.14p.u. reactive power to support POI voltage by reactive power regulation when POI voltage sags. Further, it is seen that reactive power output recovers to 0 when POI voltage recovers, which may cause minor fluctuation of POI voltage. Then POI voltage recovers to steady state.

From the above, it is seen that wind farm may supply reactive power support rapidly when POI voltage sags. Also, it can recover its reactive power capacity properly to maintain enough reactive power regulation capacity so that it is helpful to maintain POI voltage stability.

6.Conclusion

An optimization control strategy for reactive power control of wind farm is proposed. The numerical test result shows that the strategy can regulate reactive power to trace voltage fluctuation caused by small disturbances. Also, it verifies that it can supply reactive power support when fault occurs and recover reactive power output of wind farm after fault cleared according to the strategy.

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